Real-World CO_2 and NO_X Emissions from Refrigerated Vans

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Abstract:

Refrigerated vans used for home deliveries are attracting attention as online grocery shopping in the UK is expanding rapidly and contributes to the increasing greenhouse gas (CO_2) and nitrogen oxides (NO_X) emissions. These vans are typically 3.5-tonne gross weight vehicles equipped with temperature-controlled units called Transport Refrigeration Units (TRUs), which are usually powered off the vehicles' engine. It is obvious that vehicles with added weight of TRUs consume more fuel and emit more NO_X, let alone the vehicles' diesel engines are also powering the refrigeration units, which further elevates the emissions.

This research uses an instantaneous vehicle emission model PHEM (version 13.0.3.21) to simulate the real-world emissions from refrigerated vans. A validation of PHEM is included using data from laboratory (chassis dynamometer) tests over a realistic driving profile (the London Drive Cycle), to assess its ability to quantify the impact of changing vehicle weights and carrying loads. The impact of the TRU weight, greater frontal area increasing aerodynamic drag and refrigeration load on van emissions is then estimated by PHEM. The influence of ambient temperature, cargo weight and driving condition on CO_2 and NO_X emission from refrigerated van are also assessed.

Overall CO_2 emissions of vans with TRUs are found to be 15% higher than standard vehicles, with NO_X emissions estimated to be elevated by 18%. This confirms the need to take into account the impact of additional engine load when predicting van emissions in this and other sectors such as ambulances which are relatively heavy, high powered vehicles. Moreover, findings of the impact of TRUs on fuel consumptions can be used to optimize fuel-saving strategies for refrigerated vans and test cases for alternative low- or zero-emission technologies, to support progress to a sustainable net-zero society.

Keywords:

real-world emissions, light commercial vehicles, transportation refrigeration units (TRUs), PHEM, Carbon Dioxide (CO_2), Nitrogen Oxides (NO_X)

1. Introduction

Estimation of road transport emissions in the UK shows that light commercial vehicles (LCVs), or vans have seen the fastest growth in both CO_2 and NO_X emissions, accounting for 17% of CO_2 emissions and 35% of NO_X emissions in 2017 (NAEI, 2019), while van numbers only make up around 10% of total licensed vehicles (DfT, 2018b). One of the main factors contributing to the increasing van emissions is the rapid rise in the heavy class III[1] van demand (SMMT, 2019). Heavy vans are deployed for a wide range of services such as construction, refrigerated food delivery and ambulances. These vans are always with additional engine load, which is more polluting than standard, un-modified vehicles. Among all the modified vans with high-power demands, refrigerated vans are considered the most important due to their growing fleet share as online grocery continues to gain market over the recent years (Braithwaite, 2017).

Refrigerated vans are typically 3.5-tonne gross weight vehicle equipped with temperature-controlled units called Transport Refrigeration Units (TRUs), which are usually powered off the vehicles' diesel engine. It is obvious that vehicles with added weight of TRUs consume more fuel and emit more NO_X, let alone the vehicles' diesel engines are also powering the refrigeration units, which further elevate the emissions. Braithwaite (2017) suggested that there were 15,000 refrigerated vans used for grocery home delivery in the UK in 2016 and the annual distance travelled by refrigerated vans is at least twice the average (DfT, 2019). The COVID-19 outbreak has also accelerated online grocery shopping and home

[1] Vans in the UK are defined as 4-wheel vehicles constructed for transporting goods and having a gross weight of 3500kg or less. They can be further classified into three sub-categories by reference mass, where class I are vans less than 1305kg, class II are those between 1305kg and 1760kg, and class III are those above 1760kg.

delivery orders were found to grow by 38% from 2.1 million to 2.9 million per week[2] in the UK.

Despite the fact that vans have contributed a significant proportion to total UK's CO_2 and NO_X emissions, the majority of existing studies focus on the passenger car emissions (Carslaw, D.C. et al., 2013; Chen and Borken-Kleefeld, 2016; Pavlovic et al., 2016). Considering many studies have already demonstrated the gap between laboratory and real-driving emissions for passenger cars (Carslaw, D. et al., 2011; O'Driscoll et al., 2018; Tietge et al., 2019), it is expected there is a significant divergence for vans as well. Besides, all the European emission standard for vans follow passenger cars[3] by one year. Time delays between emission legislation and its effective implementation may well lead to a larger discrepancy between van emissions generated from lab test cycle and real-world driving. In order to better understand and control the negative impact of CO_2 and NO_X emissions on public health and the environment, it is considered both timely and significant to examine on-road emissions from vans.

To assess the environmental impact of vehicle exhaust pollutants, numerous emission models have been developed. Macroscopic emission models based on average speed or traffic situations (e.g. MOBILE, COPERT, HBEFA, ARTEMIS) (Smit et al., 2008) are suitable for emission estimation for national or regional inventories, but they might be unreliable when applied to local traffic situations

[2] https://www.gov.uk/government/speeches/environment-secretarys-statement-on-coronavirus-covid-19-26-april-2020

[3] The latest Euro 6d temp and Euro 6d requires light-duty vehicles to meet corresponding 'not to exceed' limits in Real Driving Emissions testing (RDE) procedure before they could be placed on the market. The RDE test has gradually taken effect since 2017 and will apply to all new passenger cars by the beginning of 2021 and all new vans by the beginning of 2022 (Commission Regulation (EU) 2017/1151).

(Ahn and Rakha, 2008). Microscopic emission models (e.g. PHEM, MOVES) (Boulter et al., 2007) better capture vehicle emission behaviour given that they require detailed input data such as second-by-second speed profile, altitude and signals, as well as the design and operation strategy of engine and powertrain (Küng et al., 2019). Microscopic models are typically used in specific user test cases and scenario testing, such as estimating the vehicle emissions of heavy goods vehicles (HGVs) in port areas (Zamboni et al., 2013), optimizing transit buses' cruising speeds range for fuel economy (Wang and Rakha, 2016), or assessing the impact of the additional engine loads of road grade on fuel consumption and exhaust emission (Wyatt, 2017). This paper uses PHEM (Passenger Car and Heavy Duty Emission Model) to estimate the emissions from refrigerated vans as it has one of the largest vehicle emission database (Zamboni et al., 2013) compared to other instantaneous emission models, and it is capable of accounting for the impact of increased weight, frontal area and refrigeration load on its emissions.

The main focus of this paper is CO_2 and NO_X emissions from refrigerated vans as CO_2 is directly linked to global warming and NO_X is detrimental to public health and the environment. Independent chassis dynamometer tests over a realistic on-road driving profile (the London Drive Cycle (Moody and Tate, 2017)) are used to validate PHEM's ability to simulate transient tail-pipe emissions and quantify the impact of changing vehicle weights and carrying loads. The emission performance of vans with additional loading of TRUs is then assessed by PHEM. The influence of ambient temperature, cargo weight and driving condition on CO_2 and NO_X emission from refrigerated van are also evaluated.

2. Method

2.1 PHEM characteristics and application to vans

PHEM is an instantaneous vehicle emission model able to simulate second-by-second fuel consumption and most relevant tail-pipe pollutant emissions based on transient engine maps (Hausberger and Rexeis, 2017). PHEM was first developed by the Institute for Internal Combustion Engines and Thermodynamics at the Graz University of Technology (TUG, AU) in late 90's and has been continually updated to include new technologies and advance the accuracy of prediction.

As input, PHEM requires a defined driving cycle (speed curve and road longitudinal gradient over time) at 1 Hz so it can calculate engine power demand from the driving resistance and losses. It requires vehicle specifications (tyre diameter, final drive and transmission ratio as well as a driver gear shift model) to simulate engine speed, with default parameters available. The engine power and engine speed are linked to an engine emission map specific to the test vehicle type, which underpins the simulation of vehicle fuel consumption and exhaust emissions (g/sec).

To represent average European vehicles, PHEM provide a set of predefined “default vehicles”, which is based on chassis dynamometer measurements from HBEFA version 4.1 database. The database covers the most common vehicle categories (passenger cars, vans, heavy duty vehicles) from Euro 0 to Euro 6 (including Euro 6a/b, Euro 6c, Euro 6d-Temp and Euro 6d) with gasoline-, diesel- and alternatively-fuelled engine. For vehicles with selective catalytic reduction (SCR) systems such as diesel Euro 6 vans, PHEM would also activate the exhaust gas after-treatment model to achieve a more accurate prediction of NO_X

emissions. In the next section, average emission data in PHEM are compared with test results of single vehicles to validate PHEM's capability to simulate second-by-second fuel consumption (CO_2) and tail-pipe emissions in defined driving cycles.

2.2 Laboratory validation

2.2.1 Driving conditions and test vehicles

Chassis dynamometer tests were conducted by Millbrook Proving Ground Ltd[4] on behalf of Transport for London (TfL) over a drive cycle called the London Drive Cycle (LDC). The tests were performed with a warm start, compliant with the requirements of current type approval regulations[5]. During the tests the exhaust pollutant was diluted continuously with ambient air using the Constant Volume Sampling (CVS) system (Costagliola et al., 2018) and the emissions were measured second-by-second using a gas analyser.

The LDC contains 9 sub-cycles, representing 3 different road types (urban, suburban and motorway) under 3 different traffic conditions (AM peak, inter peak and free-flow) (Moody and Tate, 2017). The speed profile of the LDC is illustrated in Figure 1. The drive-cycle doesn't consider fluctuations in road gradient. Measurement data from Millbrook Vehicle Emission Laboratory tested over the LDC is considered to be authentic and representative of real-world driving behaviour and vehicle emissions.

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[4] https://www.millbrook.co.uk/services/vehicle-emissions-testing-facility-powertrain/

[5] The Millbrook Vehicle Emission Laboratory is in accordance with the requirements of Directive 2007/46 EC Article 41, Section 3 and has been designated as a Category A Technical Service for Individual Vehicle Approvals (IVA)

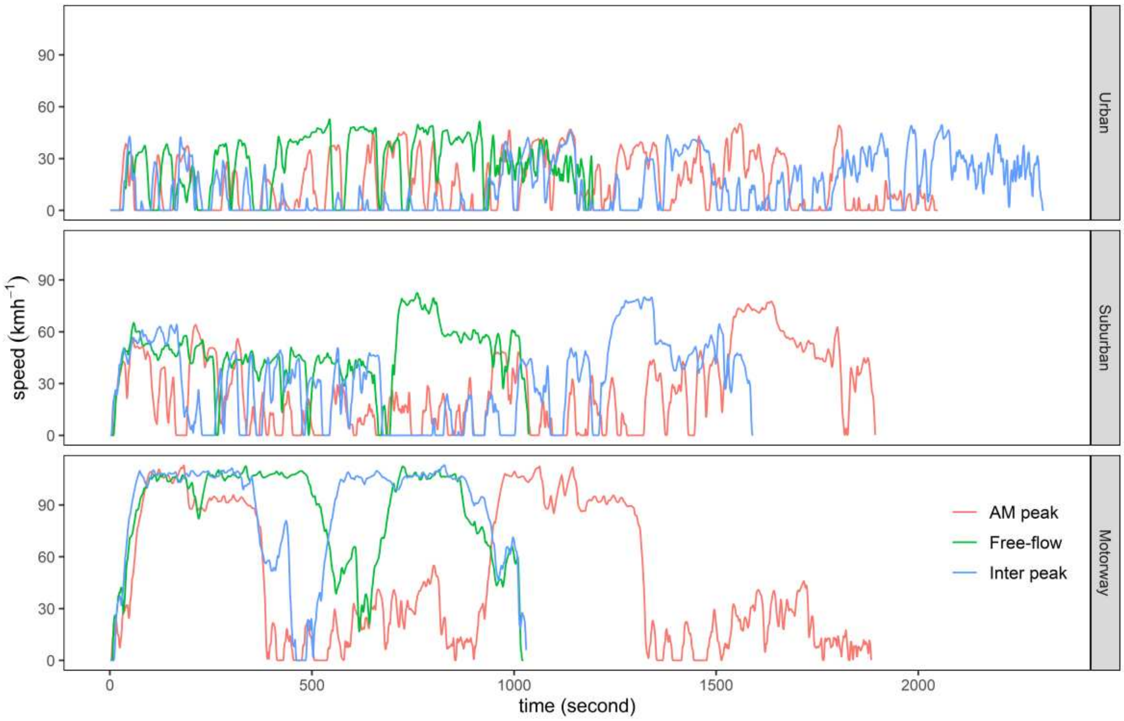


Figure 1 The London Drive Cycle speed profile

Two vehicles with different NO_X after-treatment systems were tested on chassis dynamometer over the LDC in this study. Vehicle A was a Euro 5 class III diesel LCV tested over the entire 140 km of the LDC, to verify PHEM's capability to simulate a standard van's fuel consumption and tail-pipe emission performance. Vehicle B was a Euro 6 small HGV tested over the suburban sub-cycle (free-flow and AM peak) in both un-laden (B1) and full-laden (B2) conditions. This allows PHEM's performance in quantifying the impact of changing vehicle weights and carrying loads to be evaluated. As vehicle B was a small HGV of 3450kg vehicle mass, we assume it had similar behaviours like a heavy van and is suitable for van validation. Detailed vehicle characteristics and drive cycle statistics are presented in Table 1.

Table 1 Technical specification drive cycle characteristics of each tested vehicles

Vehicle	**A**	**B1**	**B2**
Vehicle Category	N1 class III LCV	N2 HGV	N2 HGV
Vehicle Class	Euro 5 diesel	Euro 6 diesel	Euro 6 diesel
Engine Power (kw)	90	120	120
Vehicle Mass (kg)	2150	3450	3450
Vehicle Loading (kg)	375	0	4050
NO_X after-treatment system	Exhaust gas recirculation (EGR)	Selective catalytic reduction (SCR)	Selective catalytic reduction (SCR)
Road Type	Urban, Suburban, Motorway	Suburban	Suburban
Time Period	Free-flow, AM Peak, Inter Peak	Free-flow, AM Peak	Free-flow, AM Peak
Duration (s)	14019	2930	2930
Distance (km)	140	27	27
Average Speed (km/h)	35.92	32.65	32.65
Maximum Acceleration (m/s^2)	2.67	2.67	2.67

Vehicle specifications such as rated engine power, vehicle mass and vehicle loading were adjusted in PHEM's average vehicle folder to match the tested vehicles in Table 1, where vehicle A belongs to LCV N1-III and vehicle B belongs to HGV rigid truck (7.5-12ton). The LDC speed profile were also fed into PHEM to match scenarios tested in the laboratory. When comparing laboratory measurement and simulation results, the time shifts and instrument sensitivity need to be considered. In chassis dynamometer tests, tail-pipe emissions have been delayed and engine-out peaks smoothed through the exhaust analyser systems (CVS), while PHEM aims to predict the instantaneous tail-pipe emissions. In order to make laboratory measurements comparable with instantaneous simulation results, emission data from PHEM has been processed using a simple (equally weighted) moving-average method. By creating a series of averages over 2 seconds, a moving-average method is able to smooth out fluctuation in PHEM emission data and better track trend determination (Hansun, 2013). The time consistency between observed and modelled values has also been checked before validation.

2.2.2 Standard van validation

Figure 2 presents PHEM's capability to predict vehicle A's tailpipe emissions from three illustrative sample 300 second periods of the speed profile chosen to be contrasting the LDC, which include driving in: an urban setting during the AM peak (low speed, stop-start), a suburban district during inter peak (moderate speed) and a free-flow, higher speed motorway driving conditions. The observed and modelled CO_2 values (second panel) are in close agreement in all driving conditions, while the observed NO_X values (bottom panel) for the specific test vehicle are slightly higher than the modelled value in high speed driving (Motorway, Free-flow section).

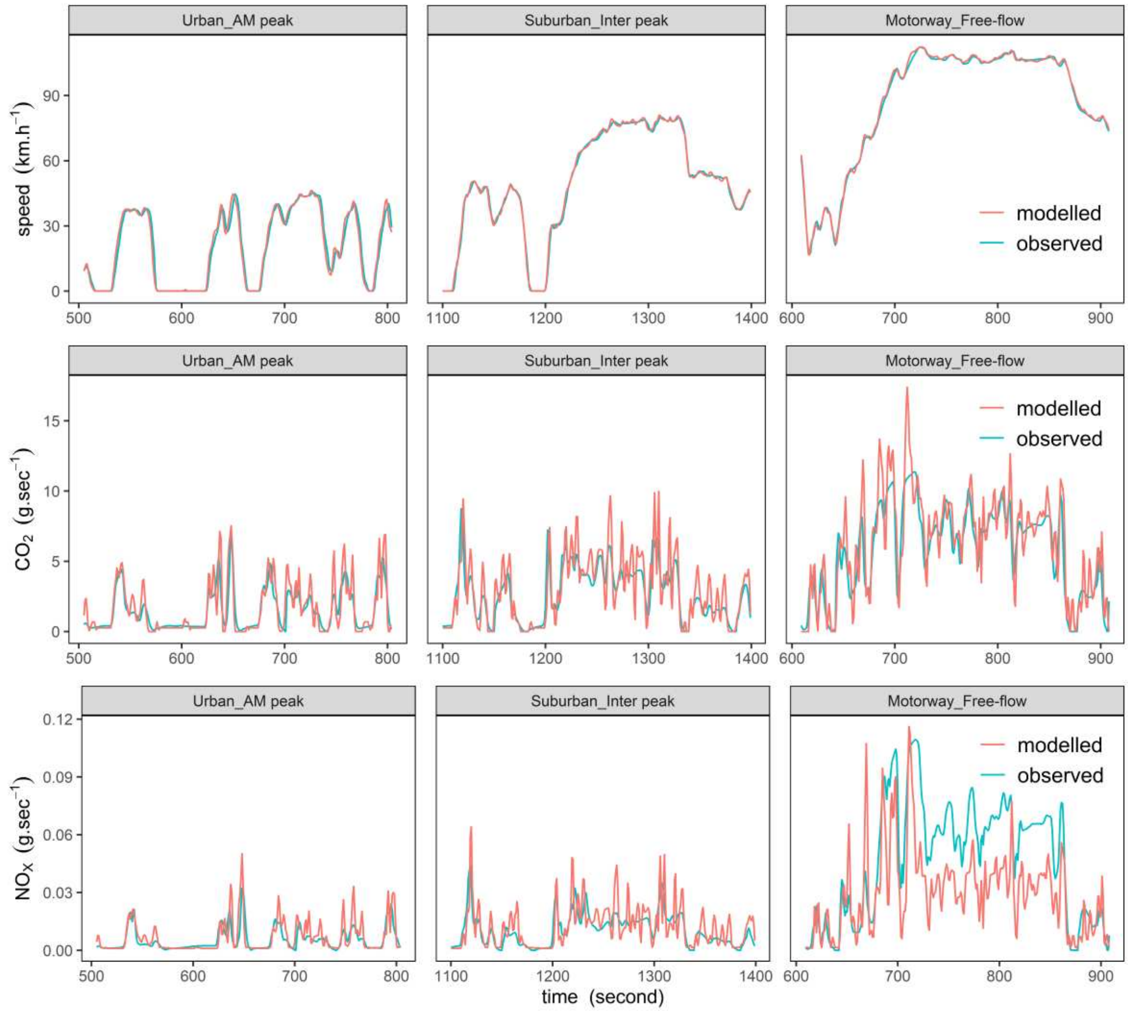


Figure 2 Illustrative time-series plot of different sections of the London Drive Cycle driven by vehicle A (a) speed (top); (b) CO_2 (middle); and (c) NO_X (bottom)

In order to study the reason behind the disagreement of observed and modelled NO_X emissions in free-flow driving conditions, we explored the impact of speed on both CO_2 and NO_X emissions and the results are illustrated in

R^2=0.84 (a) R^2=0.67 (b)

Figure 3. The second-by-second observed CO_2 and NO_X emissions are plotted against modelled CO_2 and NO_X emissions, and the emission values are grouped

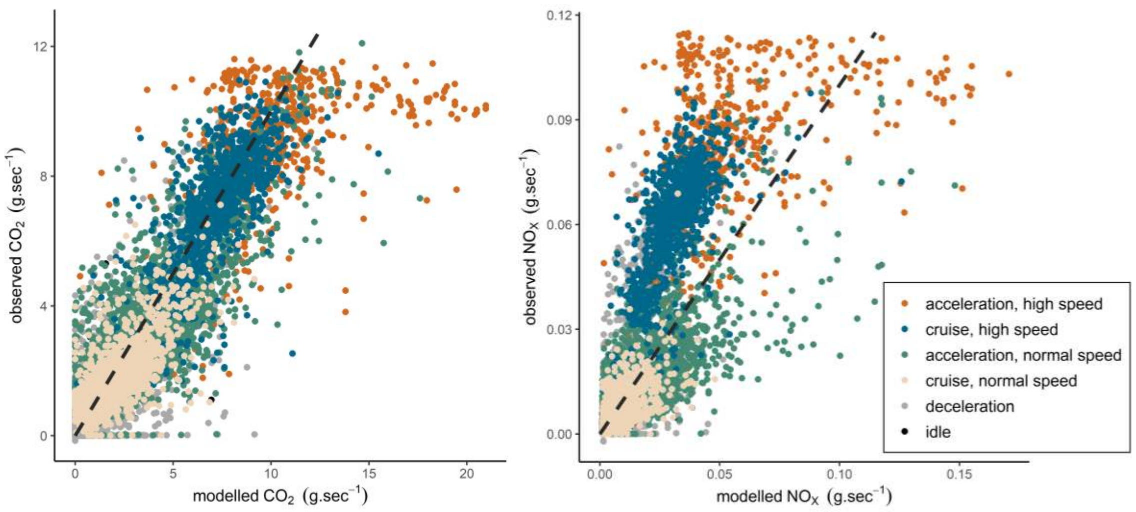
by driving mode of that corresponding second. The driving mode definitions proposed by (Moody and Tate, 2017) are used and expanded:

- Idle | vehicle speed < 0.5m/s^2 and acceleration in the range ± 0.1m/s^2;
- Cruise with normal speed | 0.5m/s^2 < vehicle speed < 22m/s^2 and acceleration in the range ± 0.1m/s^2;
- Cruise with high speed | vehicle speed > 22m/s^2 and acceleration in the range ± 0.1m/s^2;
- Acceleration with normal speed | vehicle speed < 22m/s^2 and acceleration > 0.1m/s^2;
- Acceleration with high speed | vehicle speed > 22m/s^2 and acceleration > 0.1m/s^2;
- Deceleration | acceleration < -0.1m/s^2.

R^2=0.84 R^2=0.67

(a) (b)

Figure 3 illustrate that both CO_2 and NO_X emissions shows strong dependency on driving mode. High speed (top 15% speed range in the LDC) dominates the high emission rates, due to the elevated engine power demands needed to overcome the greater aerodynamic and rolling resistances. The left plot for CO_2 emissions shows that the second-by-second observed and modelled CO_2 data is highly consistent and the coefficients of determination (R^2) between observed and modelled CO_2 is 0.84, which demonstrates PHEM's ability to deliver a reliable, transient estimation of real-world CO_2 emissions for different speed ranges. The right plot for NO_X emissions are also in close agreement with the R^2 value of 0.67, and the main deviation between observed and modelled NO_X values is at higher emission rates (> 0.03g/sec) when a more aggressive driving style (top 15% speed in cruising and accelerating driving mode) is taken. Vehicle A with a EGR after-treatment system has the most effective NO_X control performance during low engine load operation (Zheng et al., 2004). When the vehicle is driven at high speed (high engine load), it's quite challenging to predict exhaust emissions as after-treatment system performance are more variable. Moreover, PHEM engine power and emission maps are based on an average (normalised) of several vehicles of that category, and there are differences between specific vehicles and fleet averages. In this case, the tested LVC is a heavy diesel van and its engine and emission map may perform slightly worse than the average sized van of its type in PHEM.



R^2=0.84 (a)

R^2=0.67 (b)

Figure 3 comparing observed and modelled emission rates for vehicle A by driving mode (a) CO_2 (left); (b) NO_X (right). Black line denotes a 1:1 relationship between the modelled and observed emission rates (R^2=1)

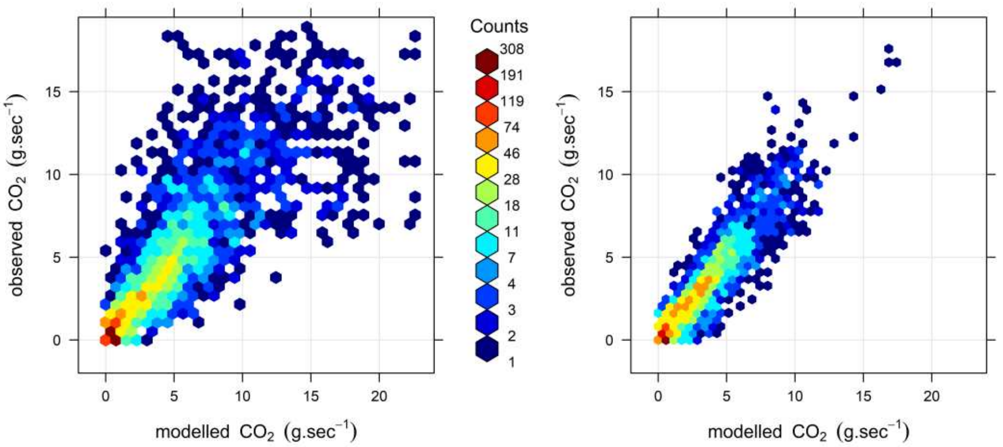
2.2.3 Loaded van validation

To assess PHEM's performance of quantifying the impact of varying load (weight), vehicle B was tested over the suburban sub-cycle (free-flow and AM peak) in both un-laden (vehicle B1) and full-laden (vehicle B2) conditions. A summary of the observed and modelled average CO_2 and NO_X emission rates is presented in Table 2. It's worth noticing that the observed NO_X emissions were highest when the un-laden vehicle was driven in AM peak with low speed, stop-and-go conditions. This is suggested to be due to low engine load (un-laden and urban driving) operations, resulting in cooler exhaust temperatures and the SCR system not meeting its operational temperature to achieve effective conversions and catalytic reductions (Koebel et al., 2002; Johnson, 2014; Moody and Tate, 2017). The observed and modelled CO_2 emission rates (g/km) are in close agreement in both un-laden and full-laden conditions, while the modelled NO_X emission rates (g/km) are roughly half those from the laboratory tests. Though PHEM failed to reliably predict the NO_X emission rates of this specific vehicle, it does capture the trend that the NO_X emissions rates in un-laden conditions are considerably higher than in full-laden conditions for each sub-cycle.

Table 2 summary of observed and modelled CO_2 and NO_X emission rates from un-laden and full-laden Euro 6 N2 HGV

Pollutant	Time period	Un-laden (g/km)		Full-laden (g/km)	
		Observed	Modelled	Observed	Modelled
CO_2	Free-flow	291.11	280.66	410.49	400.61
	AM peak	355.63	379.02	530.22	539.10
NO_X	Free-flow	0.27	0.33	0.17	0.11
	AM peak	1.08	0.41	0.46	0.16

Figure 4 presents the scatterplot of observed and modelled CO_2 values for un-laden and full-laden conditions over the chosen test cycle. The frequency of data points in a hexagonal bin is illustrated on a colour-scale, so both the range in values and where the core of the data lies are visualised. The scatterplots for CO_2 indicate that PHEM is reliably predicting the dynamics and magnitude of CO_2 emissions under both un-laden and full-laden conditions. The R^2 between 2930 simulation values and laboratory results are 0.84 and 0.71 for un-laden and full-laden conditions respectively, demonstrating PHEM's ability to quantifying the impact of carrying loads on CO_2 emissions.



R^2=0.84 (a)

R^2=0.71 (b)

Figure 4 Scatter plots of comparing modelled (PHEM) and observed CO_2 values for suburban sections in free-flow and AM peak (a) 0% payload (left); (b) 100% payload (right)

The results in former sections suggest that PHEM accurately estimates the instantaneous CO_2 emissions from both standard van and loaded small HGV (and potentially vans). Though PHEM didn't compute the instantaneous NO_X emission rates very precisely for a specific loaded HGV, it is suggested the test vehicles’ engine and emission map deviates from the average vehicle in the fleet that PHEM is attempting to represent. The model does capture the trend and dynamics of the measurements. These validation results suggest PHEM is a suitable modelling tool and capable of simulating the real-world emissions from refrigerated vans including the relative impact of TRUs.

3. Impact of TRUs on vans

3.1 Additional load of TRUs

The additional load of TRUs on the vehicle engine can be divided into three parts, added weight of the TRUs (insulation material included), increased frontal area of the condenser mounted in front of a van, the refrigeration load (additional electrical load on the engine to power belt-drive compressor). The added weight and frontal area of TRUs can be directly added to vehicle specification in PHEM, and the refrigeration load depends on many external parameters besides TRU's cooling capacity: the ambient temperature and refrigerated compartment temperature; the actual van size and engine type; the load of chilled and frozen food; insulation properties of the isothermal box; door opening times during operating; test cycle and driver's behaviour.

To capture the accurate power demand of refrigeration units under real-operating conditions, we calculate the refrigeration load based on ASHRAE (2018) thermal load calculation procedures, which divides the refrigeration load into five parts (represented in Figure 5): (1) transmission load, which is the heat transferred into the refrigerated space through its surface; (2) product load, which is the heat removed from product to keep the refrigerated space in a setting temperature; (3) infiltration air load, which is the heat gain when door opens and air enters into the refrigerated space; (4) precooling load: which is the heat removed from the insulated box and inside air; (5) other load: including heat of internal sources, equipment related load and heat released by human.

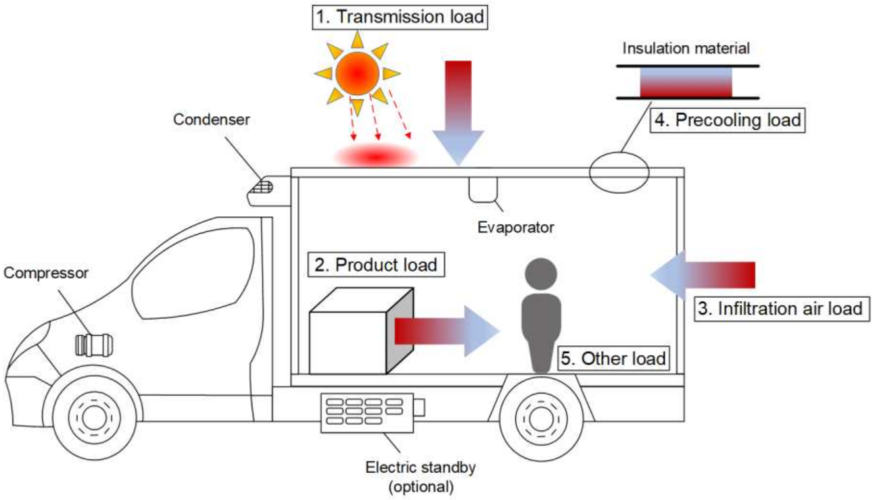
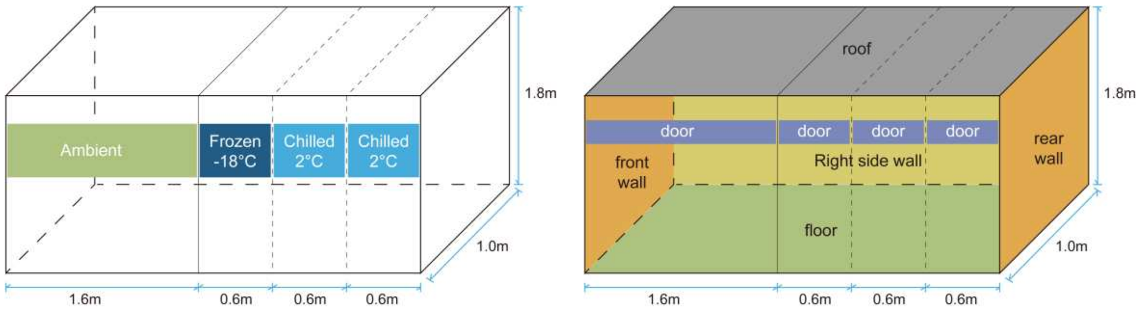


Figure 5 Main sources of heat in refrigerated van

This study uses an example to calculate the refrigeration load of the grocery delivery van and illustrate the temperature and cargo weight impact on the total refrigerated load of a refrigerated van. We consider a Euro 6a/b class III delivery van with the following specifications:

- The internal dimensions of the insulated box are 3.4m long, 1.0m wide and 1.8m high (see Figure 6-a); the box is made up with four compartments: one ambient compartment, one frozen compartment with the setting temperature of -18°C, two chilled compartments with the setting temperature of 2°C; the dimensions for each compartment is stated in Figure 6-b.
- The roof, the walls, the doors and the floor are made up of 60mm polyurethane foam (Ashida, 2006), with thermal conductivity 0.0228W/(m·K) (Tassou et al., 2009). Between each compartment an insulated bulkhead is installed, and the bulkhead is also made up of 60mm polyurethane foam.

- The total delivery time is assumed to be 8 hours per day, delivering to 4 customers per hour (figures established on interview). For every customer, the driver will keep the frozen compartment door and one of the chilled compartments door open for 1 minute.



(a) (b)

Figure 6 (a) internal dimensions and setting temperature of each compartments (left); (b) schematic diagram of the insulated box of a delivery van (right)

Only transmission load and infiltration load are considered for simplification here. The complete calculation procedure is documented in the supplementary material. In order to evaluate the impact of ambient temperature on total refrigeration load, this paper uses three illustrative temperature settings, from 40°C in the summer, 20°C in spring/autumn to 0°C in the winter. When comparing the total refrigeration load in different temperature (see Table 3), considerate reduction is found as the temperature decreases, which demonstrate the significant effect of ambient temperature on refrigeration load.

Table 3 total refrigeration load in different temperature

Temperature, °C	Transmission load, kW	Infiltration load, kW	Total refrigeration load, kW
40	0.31	2.63	2.93
20	0.18	1.75	1.93
0	0.06	0.73	0.78

3.2 Fuel consumption and exhaust emissions from refrigerated vans

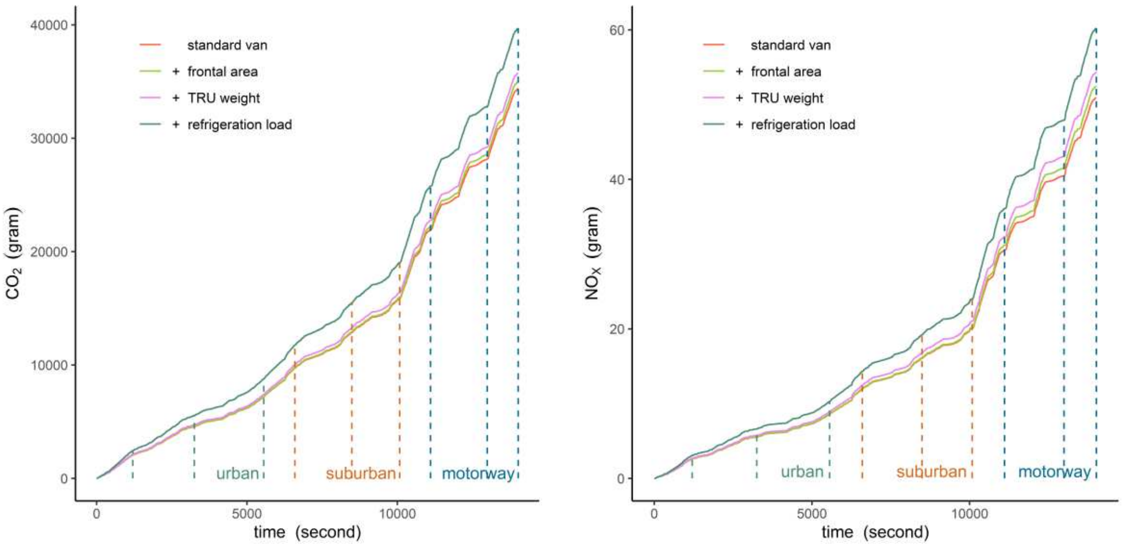
Impact of TRUs on a Euro 6a/b class III van with average loading of 375kg (default setting in PHEM) was assessed by PHEM over the LDC. When considering the additional load of TRUs, an added 135kg TRU weight, 0.23 m^2 increased frontal area and 1.93 kW refrigeration load at an ambient temperature of 20°C were added to vehicle specifications in PHEM over the full 140km LDC. These were contrasted with emissions from the same base Euro 6a/b class III standard van with 375kg loading following the same driving trajectory and conditions. In both refrigerated van and standard van simulations, the SCR module is activated, as Euro 6a/b class III van are commonly equipped with SCR after-treatment system to mitigate NO_X emissions.

Simulation results shows that average CO_2 emission for a refrigerated van is 282 g/km, 15% higher than standard van, while average NO_X emission factor for a refrigerated van is 0.43 g/km, 18% higher than standard van. The real-world CO_2 emissions from refrigerated vans is nearly 2 times the government's target (147 g/km) and NO_X emissions more than 3 times the Euro 6ab limit (0.125 g/km).

The increased frontal area, added TRU weight and additional refrigeration load were added respectively in PHEM to assess their impact on CO_2 and NO_X emissions performance.

(a) (b)

Figure 7 illustrates these additional loads over the whole LDC at an ambient temperature of 20°C, and slope in each sub-cycle represents the average emission rate per second (g/sec) for different driving conditions. It's clear that the refrigeration load contributes to the largest share of additional CO_2 and NO_X emissions.



(a) (b)

Figure 7 cumulative plot of (a) CO_2 emissions (left) and (b) NO_X emissions (right) at an ambient temperature of 20°C (different parts of TRU load)

The refrigeration loads in 3 ambient temperature scenarios specified in Table 3 were added to PHEM as auxiliary electrical engine loads, with the standard TRU increased frontal area and additional weight also applied. Table 4 summarizes the impact of ambient temperature on CO_2 and NO_X emissions from refrigerated vans, as well as the relative contribution of these three additional loads. A high ambient temperature of 40°C is found to impose a significant additional auxiliary power load for cooling, and associated increases in fuel consumption and NO_X emissions. In all ambient temperature scenarios, the refrigeration load is found to account for the majority of the additional emissions associated with equipping the vehicle with a TRU. The results demonstrate the need to minimise refrigeration load through storage compartment and door opening management/strategies, especially when ambient temperature is high, for the heat gain through the insulation box and from air infiltration when door is open and closed is considerable.

Moreover, the increase in emissions may be partly offset by a "low temperature NO_X emission penalty" found in diesel vehicles (Grange et al., 2019), where ambient temperature has an impact on diesel vehicle's post-combustion control technology and high temperature resulting in lower NO_X emissions. Vehicles equipped with LNTs (lean NO_X traps) shows more temperature dependency than vehicles with SCRs.

Table 4 Impact on the CO_2 and NO_X emissions by various ambient temperature

Pollutant	Ambient temperature, °C	Emission rates, g/km	Share of different parts in additional emissions		
			Frontal area	TRU weight	Refrigeration load
CO_2	40	297	8%	10%	82%
	20	282	11%	14%	74%
	0	265	21%	26%	53%
NO_X	40	0.45	12%	16%	72%
	20	0.43	16%	21%	62%

0	0.40	27%	35%	38%

In Table 5 two sub-cycles (free-flow and AM peak time period in suburban areas) were chosen to contrast refrigerated van's emission performance with different cargo loading under different driving conditions. Loading factors from un-laden (135kg TRU weight counted), average-laden (375kg cargo plus 135kg TRU weight) to full-laden (1265kg cargo plus 135kg TRU weight) were added in PHEM. Unlike the emission test results in the validation process in Table 2, NO_X emissions are higher in full-laden conditions than in un-laden conditions, which might be due to the fact that refrigerated vans already have additional TRU weight even in un-laden conditions, providing enough exhaust emission temperature for SCR to work efficiently. Both CO_2 and NO_X emissions are higher when vehicles were driven in AM peak traffic conditions. Further research, perhaps including chassis dynamometer test or portable emission measurement is suggested to be needed, to study the cause and impact of loading on refrigerated vans.

Table 5 the influence of grocery weight and driving condition on emission rates for a Euro 6 class III refrigerated van (20°C ambient temperature)

Pollutant	Time period	Un-laden (g/km)	Average-laden (g/km)	Full-laden (g/km)
CO_2	Free-flow	209	223	255
	AM peak	264	280	322
NO_X	Free-flow	0.27	0.30	0.39
	AM peak	0.33	0.37	0.49

Simulation results over the realistic London Drive Cycle suggest significant differences of CO_2 and NO_X emissions between standard vans and refrigerated vans. The influence of higher ambient temperatures, heavier loading factor and stop-start driving condition on emissions are is also worth attention. Findings confirm the need to take into account the impact of additional engine load when predicting refrigerated van emissions.

Aside from higher emission factors for refrigerated vans, demand for grocery home deliveries has surged since the outbreak of COVID-19, and the rise is expected to be sustained as the pandemic has brought new customer to online grocery and many would retain the habit. Mintel[6] estimates the market to be worth £17.9 billion by 2024, growing by 41% over the five year period, resulting in a significant growth and associated environmental impact of refrigerated vans.

[6] https://www.mintel.com/press-centre/retail-press-centre/mintel-forecasts-online-grocery-sales-will-grow-an-estimated-33-during-2020

4. Summary and conclusions

Analysis conducted in this study aims to understand the contribution of TRUs to CO_2 and NO_X emissions from vans. By simulating the CO_2 and NO_X emissions of vehicles measured on the chassis dynamometer, PHEM has been proven to be a model capable of estimating instantaneous emissions for vehicles carrying loads. Real-world CO_2 and NO_X emission factors for refrigerated vans have been developed using PHEM, and the analysis highlights the following findings:

- Vans with TRUs generate ≈15% more CO_2 emissions and ≈18% more NO_X emissions than standard vans.
- The impact of TRU weight, frontal area and electrical load on the engine by the TRU on emissions were independently assessed, illustrating that the refrigeration load is the most significant cause of excess emissions, contributing increase of 74% and 62% to CO_2 and NO_X emissions respectively.
- The burden of additional emissions of a TRU van becomes more significant in higher ambient temperature as the refrigeration load increases. Stop-start driving conditions and heavier cargo loading are also shown to elevate emissions.

Analysing the difference between standard van and refrigerated van by PHEM is important in three ways. Firstly, simulation results confirm the need to take into account the effect of additional load when predicting refrigerated van emissions and fuel consumption. Secondly, findings on the impact of temperature, grocery loading and driving conditions on refrigerated van emissions can be used to improve fuel-saving and eco-friendly strategies in grocery delivery. Moreover, PHEM is capable of evaluating the impact of real-world factors on emissions.

Local policy makers can adjust the vehicle parameters so that they are specific to their own applications and situations.

Van traffic is forecast to continue growing significantly and make up between 14% and 21% of traffic mileage by 2050 (DfT, 2018a), in the meanwhile results in this study suggests that real-world emission factors of standard vans are higher than official statistics. It is both timely and significant to accurately assess the real-world van emissions as city authorities consider whether to include restrictions on vans in policies such as Low Emission and Clean Air Zones (Defra, 2018; DfT, 2020).

Recommendations for further research include laboratory (chassis dynamometer) test for refrigerated vans under different scenarios, to study the impact of changing ambient temperature, door opening times or weight of cargo. A special test (drive) cycle could also be designed to assess the influence of driving conditions and refrigeration unit designs/operation. Besides, further research could also focus on the environmental impact from all the other kinds of vans with extra loading, like ambulances which are always high powered and heavy loaded, and to include different measurement or estimation methods like laboratory (chassis dynamometer) testing, on-road (PEMS), remote sensing and simulations.

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